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OFT Ascent/Descent Ancillary Data Requirements Document

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SHUTTLE PROGRAM

OFT ASCENT/DESCENT ANCILLARY
DATA REQUIREMENTS DOCUMENT

By A. C. Bond, Jr., Mathematical Physics Branch and
J. Knoedler, TRW

Approved: ______________________
Emil R. Schiesser, Chief
Mathematical Physics Branch

Approved: ______________________
Ronald L. Berry, Chief
Mission Planning and Analysis Division

Mission Planning and Analysis Division

National Aeronautics and Space Administration

Lyndon B. Johnson Space Center

Houston, Texas

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TABLES

FIGURES

ACRONYMS

A/D	ascent/descent
AOA	abort once around
ATO	abort to orbit
att.	attitude
BET	best estimated trajectory
CCT	computer compatible tape
DFI	development flight instrumentation
DRC	data reduction complex
ET	external tank
FTR	flight test requirement
G&N	guidance and navigation
GDSD	Ground Data Systems Division
GMT	Greenwich mean time
HS	high-speed
IDSD	Institutional Data Systems Division
IMU	inertial measurement unit
lb	pounds (force)
MCC	Mission Control Center
MECO	main engine cutoff
MPAD	Mission Planning and Analysis Division
MPB	Mathematical Physics Branch
NMC	National Meteorological Center
OFT	orbital flight test
OI	operational instrumentation
OMS	orbital maneuvering system
RTLS	return-to-landing site
SRB	solid rocket booster
TM	telemetry

1.0 INTRODUCTION

This document contains requirements for the ascent/descent (A/D) navigation and attitude-dependent ancillary data products to be generated for the Space Shuttle Orbiter by the Mathematical Physics Branch/Mission Planning and Analysis Division (MPB/MPAD) in support of the orbital flight test (OFT) flight test requirements (FTR's), MPAD guidance and navigation (G&N) performance assessment, and the mission evaluation team. This document is intended to serve as the sole requirements control instrument between MPB/MPAD and the A/D ancillary data users. The requirements presented herein are primarily functional in nature, but some detail level requirements are also included.

2.0 ASCENT/DESCENT ANCILLARY DATA SUPPORT SCOPE

The A/D ancillary data support for OFT mission evaluation activities shall be confined to providing postflight position, velocity, attitude, and associated navigation and attitude derived parameters for the Orbiter over the flight phases and time intervals shown in figure 1. No ancillary data support related to the external tank (ET) or the solid rocket boosters (SRB's) shall be provided. In addition, the A/D ancillary data products delivered shall be confined to those described in section 5.0 of this document.

3.0 DATA PROCESSING APPROACH (FOR INFORMATION)

This section summarizes the A/D ancillary data processing approach in terms of the functional flow diagram shown in figure 2. The approach is presented primarily for information purposes to acquaint prospective ancillary data users with the current data reduction plan. Elements of the approach are subject to change, pending further analyses of data processing techniques and procedures.

3.1 INPUT DATA SOURCES AND INITIAL DATA PRODUCTS (TIER 1)

Raw C- and S-band tracking data shall be obtained from the OFT Mission Control Center (MCC) through the facilities of the Ground Data Systems Division (GDSD). Selected onboard navigation and attitude telemetry data shall be obtained from the Institutional Data Systems Division/Data Reduction Complex (IDSD/DRC).

Phototheodolite data shall not be processed in this task.

3.2 INTERMEDIATE DATA PRODUCTS (TIER 2)

Preprocessing or conditioning of the input tracking and telemetry data shall be accomplished by using interactive computer graphics techniques. Ground and onboard clock times shall be tabulated to implement correlation of sensor data from the two input sources. Special event times will be provided by the JSC Instrumentation Integration Branch (WC6).

3.3 FINAL PROCESSING AND DELIVERED OUTPUT DATA PRODUCTS (TIERS 3, 4, AND 5)

At the tier-3 level, an ephemeris solution (position, velocity, and acceleration) shall be generated first, using a navigation filter procedure that combines onboard and ground tracking data in the A/D flight regions area. (Both sources are available.) In regions where ground tracking is precluded (e.g., during entry blackout), the solution shall be obtained by using onboard inertial measurement unit (IMU) data to propagate the state vector computed at the terminus of the navigation filter solution. Attitude data are then refined and time-correlated with the overall ephemeris solution. This result shall provide the basis for the delivered output products indicated in tier 4.

Tier-4 processing shall include the computation of the remaining navigation and attitude-related parameters needed to complete the parameter set established for the output product; i.e., the product intended to satisfy the ancillary data users. Ascent quick-look output data will be provided in this tier. The basic computation for the ascent quick-look outputs is the same as the final outputs with the exception of enhanced BET accuracy. The final descent best estimated trajectory (BET) is developed in tier 4 and reflects the meteorological data supplied to MPAD by WC6.

MSFC via WC6 will provide the meteorological data for the ascent segment of the OFT flights. These data will be provided by MSFC 5 days after flight phase termination. The meteorological data for the descent phase will be supplied by the National Meteorological Center (NMC) 3 weeks after the OFT flight via WC6. The NMC requires plots and tabulation of the descent ground track based on telemetry (TM) vectors for generating the meteorological data. A time history of center-of-gravity data for the ascent and descent segment of the OFT flights will also be provided by WC6. This information will be reflected in the ascent final and quick-look product.

In association with the ascent and descent BET's, a set (table I(c)) of navigation parameter accuracies will be generated as a special product that gives an estimate of the error associated with the tier-3 outputs, which includes the uncertainty associated with the observed meteorological data provided by the MSFC and NMC via WC6.

4.0 REQUIRED INPUTS

Raw C- and S-band tracking data shall be obtained from the OFT MCC through the facilities of the GDSD. Selected onboard navigation and attitude telemetry data shall be obtained from the IDSD/DRC.

MSFC via WC6 will provide the meteorological data and associated accuracies for the ascent segment of the OFT flights. These data will be obtained by MSFC through KSC.

Meteorological data and associated accuracies for the descent phase will be supplied by the NMC 3 weeks after the OFT flights. The NMC requires plots and tabulation of the descent ground track (latitude and longitude) based on TM vectors for generating the meteorological data. Special event times will be provided by WC6.

In order that the task provide velocity and acceleration vector data with respect to the vehicle center of mass, the task requires as input a table that defines the location of the center of mass with respect to the navigation base. The definition of the center of mass with respect to the IMU navigation base will be coordinated through WC6.

5.0 GENERAL ORBITER ASCENT/DESCENT OUTPUT PRODUCTS

Functional as well as some detail level characteristics are presented here for the Orbiter ascent/descent ancillary output products. Both general and special ancillary output products are addressed in terms of the following output requirement items:

a. Parameters

b. Coordinate systems

c. Units

d. Accuracies

e. Time correlation

f. Output data frequency

g. Output data forms

h. Data product delivery schedules

i. Data product distribution

5.1 GENERAL OUTPUT PRODUCTS

The output product described below is designed to provide Orbiter ascent/descent ancillary data to satisfy users with a single product. The product output parameters and format will be common to all Orbiter ascent and descent flight phases (tables I and II).

5.1.1 Parameters, Coordinate Systems, and Units

Table I(a) provides the BET output product tape format. Table I(b) describes the output tape header record. The product output parameters and their associated coordinate systems and units are given in table I(c). Definitions of the relevant coordinate systems are given in the appendix, together with equations for selected output parameters to supplement their tabular descriptions. The product ephemeris parameters in table I(c) all describe the motion of the Orbiter in navigation base and in terms of the center of mass. Table I(d) describes the BET products listing format.

There are some parameters that are output in several coordinate systems and have identical descriptions. These parameters are vector quantities whose components depend on the reference coordinate system. The following gives the generic description and a more complete definition:

a. Contact acceleration - The acceleration of the vehicle, excluding gravitational acceleration.

b. Gravitational acceleration - The acceleration of the vehicle caused by the Earth's gravitational force acting on the vehicle. The gravitational acceleration is computed by using a gravitational field model (appendix, p. A-21).

c. Total acceleration - A vector sum of the contact and gravitational accelerations.

d. Earth-relative velocity - The velocity of the vehicle with respect to the Earth-fixed coordinates (inertial velocity minus $\omega \times R$, the Earth rotation vector crossed into the inertial position vector).

e. Wind-relative velocity - The velocity of the vehicle with respect to the air mass through which it is moving. The vector is a result of subtracting the wind vector from the Earth-relative velocity vector. The wind vector, if not measured directly, is set to zero.

Tables II(a) through II(e) presents the "one-time-only" parameters for block outputs. Table II(a) presents the navigation block output format. The tape header record is given in table II(b). The output tape parameter location is presented in table II(c) with their respective description in table II(d). Table II(e) contains the output listing format. These parameters will remain constant during the duration of the mission phase.

5.1.2 Accuracies

The product generated by this task will satisfy the FTR accuracy requirements to the extent possible based on the quality of the onboard and ground navigation sensor data available.

5.1.3 Time Correlation

Time correlation of the product output variables shall be accomplished as indicated in sections 3.2 and 3.3.

5.1.4 Output Data Frequency

Product output data shall be generated at one sample per second on the even seconds Greenwich mean time (GMT) and at requested event times provided by WC6.

5.1.5 Output Data Forms

Product output data shall be delivered on Univac 1108 and CDC Cyber computer-compatible tape(s) (CCT's) accompanied by computer printout and microfilm listings. Tables I(a) through I(d) present the BET output product tape format, (table I(a)), the header record (table I(b)), the parameters, and associated word number and symbol (table I(c)) as well as the computer printout listing format (table I(d)). Tables 2(a) through 2(c) provide similar information as tables I(a) through I(d) but for the navigation block output parameters.

5.1.6 Data Product Delivery Schedules

The ascent quick-look product output shall be made available for distribution nominally 1 week after the flight phase. The final output product for ascent will be delivered 4 weeks after the flight phase and for descent, 5 weeks after the flight phase. All deliverables are dependent on receiving the required inputs.

5.1.7 Data Product Distribution

Distribution of the product output shall be accomplished as follows:

a. WC6 shall serve as the sole distribution center for all product output.

b. Requests for the data shall be made to WC6 where the appropriate JSC facilities will be directed to generate the required number of tape copies and/or listings of the tape(s).

c. MPB shall provide WC6 with the appropriate tape reel numbers, a computer printout listing of the tape(s), and a microfilm of the listing.

d. MPB shall provide IDSD with a copy of the actual tape(s).

e. MPB shall maintain the responsibility for proper archiving of the ascent/descent ancillary data.

5.2 SPECIAL OUTPUT PRODUCTS

Special output products are defined to be those requested by a small number of postflight analysts whose ancillary data requirements are not satisfied by the general output product.

5.2.1 Parameters, Coordinate Systems, and Units

Time histories of the estimated accuracy associated with a subset of the general product parameters of table I(c) shall be provided. The subset is identified in table I(c). The accuracy estimates of the BET will reflect the uncertainties associated with the measured winds and atmospheric parameters. Plots and tabulations of the descent ground track will be provided to NMC via WC6 for the development of the entry wind and atmosphere profile. Another support item that will be provided under special output is a quick-look time history of the altitude and Earth-fixed velocity magnitude of the descent trajectory based on downlinked telemetry data.

Coordinate systems and units of the latitude, longitude, altitude, and Earth-fixed velocity magnitude and navigation parameter accuracy outputs shall be identical to those defined for the general product parameters.

5.2.2 Accuracies

The product generated by this task will satisfy the FTR accuracy requirements to the extent possible based on the quality of the onboard and ground navigation sensor data available.

5.2.3 Time Correlation

There is no requirement for the special outputs to be time correlated with respect to each other, but they shall be time tagged.

5.2.4 Output Data Frequency

The parameter accuracy estimates output rates will be at least approximately every 20 seconds. Outputs for the ground track and stripped telemetry parameters will be at the rate of the downlink data.

5.2.5 Output Data Forms

Output data forms will consist of computer printout CCT plots based on the appropriate user requirements.

5.2.6 Data Product Delivery Schedules

The ground track and stripped telemetry parameters will be available 1 week after the flight. The accuracy estimates shall be distributed 3 weeks after delivery of the descent general product.

5.2.7 Data Product Distribution

Distribution of the discrete event special product shall be accomplished as discussed in section 5.1.7.

TABLE I.- ORBITER PRODUCT OUTPUT PARAMETERS

(a) BET output products tape format

Record number	Description of contents	Version: CDC 1600 BPI 9 track written by CDC	Version: Univac 800 BPI 9 track written by CDC
1	Header record 804 characters of Hollerith data. Content described in table I(b)	80 CDC S.P. word (60 bit) binary record (10 character/word) (Cyber code)	134 Univac S.P. word (36 bit) binary record (6 character/word) (Field data code)
2	First blocked binary record = first 4 BET output product tape records. Parameter content desribed in table I(c)	1000 CDC S.P. word (60 bit) binary record	1000 Univac D.P. word (72 bit) binary record
. . .		1000 CDC S.P. word (60 bit) binary record	1000 Univac D.P. word (72 bit) binary record
N	Last blocked binary record = up to 4 BET output vs. time records	1000 CDC S.P. word (60 bit) binary record	1000 Univac D.P. word (72 bit) binary record
EOF			
EOF			

Note: a. Missing quantities will be represented by -9999.

b. Parameter uncertainty values, except meteorological parameter uncertainties will only be included in the accuracy analysis output.

TABLE I.- Continued

(b) BET output products tape header record

OFT number
Flight launch date: Greenwich year, day (midnight prior to launch)
Title:
Ascent Quick-Look BET Output Products or Ascent Final BET Output Products or Descent Final BET Output Products or Ascent BET Accuracy Analysis or Descent BET Accuracy Analysis
Data start and stop time in GMT seconds from midnight prior to launch
Data rate
Comments

TABLE I.- Continued

(c) BET output product parameters

Word	Symbol	Description	Appendix figure reference	Unit
1	GET	Ground elapsed time from SRB ignition	N/A	sec
2,3,4,5	GMT	Greenwich mean time	N/A	day;hr;min;sec from midnight
6,7,8,9	SGMT	Shuttle Greenwich mean time	N/A	day;hr;min;sec from midnight
10	YEAR	Calendar year	N/A	year
		Inertial (mean of 1950) components (nav base)	A-1	
11,12,13	XM,YM,ZM	Position		ft
14,15,16	XDM,YDM,ZDM	Velocity		ft/sec
17,18,19	XDDM,YDDM,ZDDM	Contact acceleration		ft/sec^2
		Inertial (mean of 1950) components (center of mass)	A-1	
20,21,22	XMC,YMC,ZMC	Position		ft
23,24,25	XDMC,YDMC,ZDMC	Velocity		ft/sec
26,27,28	XDDMC,YDDMC,ZDDMC	Contact acceleration		ft/sec^2
		Earth-fixed Greenwich true-of-date components (nav base)	A-3	
29,30,31	XG,YG,ZG	Position		ft
32,33,34	XDG,YDG,ZDG	Velocity		ft/sec
35,36,37	XDDG,YDDG,ZDDG	Contact acceleration		ft/sec^2
38,39,40	XDDTG,YDDTG,ZDDTG	Total acceleration		ft/sec^2
41,42,43	XDDGG,YDDGG,ZDDGG	Gravitational acceleration		ft/sec^2
44,45,46	XDGW,YDGW,ZDGW	Wind-relative velocity		ft/sec
		Earth-fixed Greenwich true-of-date components (center of mass)	A-3	
47,48,49	XGC,YGC,ZGC	Position		ft
50,51,52	XDGC,YDGC,ZDGC	Velocity		ft/sec
53,54,55	XDDGC,YDDGC,ZDDGC	Contact accelerations		ft/sec^2
56,57,58	XDGWC,YDGWC,ZDGWC	Wind-relative velocity		ft/sec

TABLE I.- Continued

(c) Continued

Word	Symbol	Description	Appendix figure reference	Unit
		Runway components (nav base)	A-6	
59,60,61	XLF,YLF,ZLF	Position		ft
62,63,64	XDLF,YDLF,ZDLF	Velocity		ft/sec
65,66,67	XDDLF,YDDLF,ZDDLF	Contact acceleration		ft/sec^2
		Topodetic components (nav base)	A-5	
68,69,70	XDTD,YDTD,ZDTD	Velocity		ft/sec
71,72,73	XDDTD,YDDTD,ZDDTD	Contact acceleration		ft/sec^2
74,75,76	XDTDU,YDTDU,ZDTDU	Uncertainty in velocity		ft/sec
77,78,79	XDDTDU,YDDTDU,ZDDTDU	Uncertainty in contact acceleration		ft/sec^2
80,81,82	XDTDW,YDTDW,ZDTDW	Wind-relative velocity		ft/sec
		Body coordinate components (nav base)	A-8	
83,84,85	XDB,YDB,ZDB	Velocity		ft/sec
86,87,88	XDDB,YDDB,ZDDB	Contact acceleration		ft/sec^2
89,90,91	XDBWC,YDBWC,ZDBWC	Wind-vectors		ft/sec
92,93,94	XDBW,YDBW,ZDBW	Wind-relative velocity		ft/sec
95,96,97	XDBU,YDBU,ZDBU	Uncertainty in velocity		ft/sec
98,99,100	XDDBU,YDDBU,ZDDBU	Uncertainty in contact acceleration		ft/sec^2
101,102,103	XDBWCU,YDBWCU,ZDBWCU	Uncertainty in wind vectors		ft/sec
104,105,106	XDBWU,YDBWU,ZDBWU	Uncertainty in wind-relative velocity		ft/sec
107,108,109 110	Q1,Q2,Q3,Q4	Quaternion elements Q1,Q2,Q3,Q4, from mean of 1950 to body, from preferred IMU corrected for misalinement and drift errors	A-7	
111	PIMU	Preferred IMU	N/A	
		Plumbline inertial launch site components (nav base)	A-13	
112,113,114	XE,YE,ZE	Position		ft
115,116,117	XDE,YDE,ZDE	Velocity		ft/sec
118,119,120	XDDE,YDDE,ZDDE	Contact acceleration		ft/sec^2
121,122,123	XEU,YEU,ZEU	Uncertainties in position		ft
124,125,126	XDEU,YDEU,ZDEU	Uncertainties in velocity		ft/sec
127,128,129	XDDEU,YDDEU,ZDDEU	Uncertainties in contact acceleration		ft/sec^2

TABLE I.- Continued

(c) Continued

Word	Symbol	Description	Appendix figure reference	Unit
		Plumbline inertial launch site components (nav base) - Concluded	A-13	
130,131,132	XDEW,YDEW,ZDEW	Wind-relative velocity		ft/sec
133,134,135	XDEWU,YDEWU,ZDEWU	Uncertainties in wind-relative velocity		ft/sec
		Plumbline inertial launch site components (center of mass)	A-13	
136,137,138	XEC,YEC,ZEC	Position		ft
139,140,141	XDEC,YDEC,ZDEC	Velocity		ft/sec
142,143,144	XDDEC,YDDEC,ZDDEC	Contact acceleration		ft/sec^2
145,146,147	XDECW,YDECW,ZDECW	Wind-relative velocity		ft/sec
		Euler angles, orientation of body axes with respect to local vertical/local horizontal. Uncertainties based on preferred IMU attitude corrected for misalinement and drift errors	A-8	
148,149	ψ,ψu	Yaw and uncertainty		deg
150,151	θ,θu	Pitch and uncertainty		deg
152,153	ϕ,ϕu	Roll and uncertainty		deg
154,155	R,Ru	Yaw rate and uncertainty		deg/sec
156,157	Q,Qu	Pitch rate and uncertainty		deg/sec
158,159	P,Pu	Roll rate and uncertainty		deg/sec
160	BA	Bank angle, angle of roll about wind-relative velocity vector	A-5	deg
161	λ	Geodetic longitude	A-4	deg
162	ϕD	Geodetic latitude		deg
163,164	h,hu	Geodetic altitude and uncertainty		ft
165,166	hD,hDu	Geodetic altitude rate and uncertainty		ft/sec
167	DELTA	Angle between radius vector and equatorial plane (declination), positive north		deg

TABLE I.- Continued

(c) Continued

Word	Symbol	Description	Appendix figure reference	Unit
168	RM	Magnitude of mean of 1950 position vector	A-2	ft
169	VM	Inertial velocity magnitude	A-2	ft/sec
170	γM	Inertial flightpath angle	A-2	deg
171	ψM	Inertial azimuth (heading) angle	A-2	deg
172	RS	Slant range from vehicle to launch pad (ascent) or to runway coordinate system origin (descent)	A-6	ft
173-181	A (3x3)	Direction cosines, mean of 1950 to body coordinates based on preferred IMU attitude corrected for misalinement and drift errors	N/A	n.d.
182,183	VTD,VTDU	Wind-relative velocity magnitude and uncertainty	A-5	ft/sec
184,185	γTD,γTDU	Wind-relative (local) flightpath angle and uncertainty	A-5	deg
186,187	ΨTD,ΨTDU	Wind-relative (local) azimuth heading angle and uncertainty	A-5	deg
188	S	Earth surface range from vehicle to launch pad (ascent) or to runway coordinate system origin (descent)	A-9	ft
189,190	α,αU	Wind-relative angle of attack and uncertainty	A-8	deg
191,192	β,βU	Wind-relative sideslip angle and uncertainty	A-8	deg
193,194	$\bar{q}$,$\bar{q}$U	Wind-relative dynamic pressure and uncertainty	A-10	lb/ft^2

TABLE I.- Continued

(c) Concluded

Word	Symbol	Description	Appendix figure reference	Unit
195	$\bar{q}\alpha$	Wind-relative pitch dynamic pressure	N/A	lb-deg/ft^2
196	$\bar{q}\beta$	Wind-relative yaw dynamic pressure	N/A	lb-deg/ft^2
197,198	M,MU	Wind-relative Mach number and uncertainty	A-10	n.d.
199,200	$\bar{V}'_\infty, \bar{V}'_\infty$ U	Wind-relative viscous parameter and uncertainty	A-11	n.d.
201,202	T,Tu	Ambient temperature and uncertainty	N/A	deg R
203,204	PR,PRU	Ambient pressure and uncertainty	N/A	lb/ft^2
205	ρ	Density	N/A	slugs/ft^3
206,207	EAS,EASU	Wind-relative equivalent airspeed and uncertainty	A-12	ft/sec
208	L	Wind-relative total load factor	A-12	n.d.
209	D/M	Wind-relative drag over mass	A-12	ft/sec^2
210	LOD	Wind-relative lift over drag	A-12	n.d.
211-250	--	Spares	--	--

TABLE I.- Continued

(d) BET output products listing format

GET: 1 GMT: Date 2/10	3:	4:	5		SGMT:	DAY	6 7:	8:	9	PIMU:	111
	X	Y	Z	XD	YD	ZD	XDD	YDD	ZDD		
M50NB	11	12	13	14	15	16	17	18	19	RM	168
M50CG	20	21	22	23	24	25	26	27	28	VM	169
GTOFDNB	29	30	31	32	33	34	35	36	37	GM	170
GTOFDNB WIND REL VEL & TOT. ACC				44	45	46	38	39	40	PM	171
GTOFDNB GRAV ACC							41	42	43		
GTOFDCG	47	48	49	50	51	52	53	54	55		
GTOFDCG WIND REL VEL				56	57	58					
RUNWAY	59	60	61	62	63	64	65	66	67		
TOPDETIC				68	69	70	71	72	73	VTD	182
TOPDETIC VELU & ACCU				74	75	76	77	78	79	GTD	184
TOPDETIC WIND REL VEL				80	81	82				PTD	186
BODYNB				83	84	85	86	87	88	VTDU	183
BODYNB VELU & ACCU				95	96	97	98	99	100	GTDU	185
BODYNB WIND VECTOR				89	90	91				PTDU	187
BODYNB WIND VECTORU				101	102	103					
BODYNB WIND REL VEL				92	93	94					
BODYNB WIND REL VELU				104	105	106					
PLUMNB	112	113	114	115	116	117	118	119	120		
PNUMNBU	121	122	123	124	125	126	127	128	129		
PLUMB WIND REL VEL				130	131	132					
PLUMB WIND REL VELU				133	134	135					
PLUMCG	136	137	138	139	140	141	142	143	144		
PLUMCG WIND REL VEL				145	146	147					
LAT 162	LON 161			H 163			HD 165			DELTA 167	
RS 172	S 188			HU 164			HDU 166				

TABLE I.- Concluded

(d) Concluded

Quaternions			Direction cosines					Pitch	Yaw		Roll
Q1	107		173	174		175	EULER	150	148		152
Q2	108		176	177		178	EULERU	151	149		153
Q3	109		179	180		181	EULERD	156	154		158
Q4	110						EULERDU	157	155		159
ALPHA	189	Q	193		EAS	206	VISC	199	TEMP	201	
ALPHAU	190	QU	194		EASU	207	VISCU	200	TEMPU	202	
BETA	191	QALPHA	195		MACH	197	L	208	PRESS	203	
BETAU	192	QBETA	196		MACHU	198	D/M	209	PRESSU	204	
BANK	160						LOD	210	DENS	205	

NOTE: The numbers shown in the chart next to the mneumonic correspond with the word number used for each parameter as listed in table I(c). Missing data are indicated by blanks. Uncertainty values, except for meteorological parameters, are only included for the Accuracy Analysis output. Each page will display the complete set of data for one time point.

Two cover sheets will be attached to the listing and each will note the launch date, OFT number, listing title (Ascent or Descent, Quick-Look BET, Final BET, or Accuracy Analysis Output Products). The top cover sheet will be arranged like this chart, which shows the parameter word number in the parameter value location. The second cover sheet, in the same format, will show the units used in the parameter value location.

TABLE II.- NAVIGATION BLOCK OUTPUT PARAMETERS

(a) Navigation block output tape format

Record number	Description of contents	Version: CDC 1600 BPI 9 track written by CDC	Version: Univac 800 BPI 9 track written by CDC
1	Header record 804 characters of Hollerith data; see table II(b)	800 CDC S.P. Word (60 bit) binary record (Cyber code)	134 Univac S.P. (36 bit) binary record (6 character/ word) (Field data code)
2	Navigation block output parameters. Parameter tape location; see table II(c) parameter description; see table II(d)	1000 CDC S.P. word (60 bit) binary record	1000 Univac D.P. word (72 bit) binary record
. . .		1000 CDC S.P. word (60 bit) binary record	1000 Univac D.P. word (72 bit) binary record
29		1000 CDC S.P. word (60 bit) binary record	1000 Univac D.P. word (72 bit) binary record
E.O.F.			
E.O.F.			

NOTE: Missing quantities are represented by -9999.

TABLE II.- Continued

(b) Navigation block output tape header record

OFT number

Flight launch date: Greenwich year, day (midnight prior to launch)

Title:

Ascent Quick-Look Navigation Block
or Ascent Final Navigation Block
or Descent Final Navigation Block

Comments

TABLE II.- Continued

(c) Navigation block output tape parameter location

Item	Number of elements in array	Location			
		First word		Last word	
		Record/subscript		Record/subscript	
Guidance release time (4)	4	2	1	2	4
CGT (4,200)	800	2	5	2	804
SET (16,200)	3200	2	805	6	4
REF (27)	27	6	5	6	31
TRAC (6,100)	600	6	32	6	631
MET (20,1000)	20000	6	632	26	631
KAPPA	1	26	632	26	632
PHIO	1	26	633	26	633
DELTA	1	26	634	26	634
LAMO	1	26	635	26	635
RSUBO	1	26	636	26	636
XSUBO	1	26	637	26	637
NAVO(3)	3	26	638	26	640
SPARES	2360	26	641	28	1000

TABLE II.- Continued

(d) Navigation block output tape parameter description

Parameter	Description
Guidance release time (4)	Time when all three IMU's are released (go inertial), GMT seconds from midnight prior to launch
CGT (4,200)	Shuttle center of gravity history data T_1, T_2 - - - - - - - - - T_{200} X_1, X_2 - - - - - - - - - X_{200} Y_1, Y_2 - - - - - - - - - Y_{200} Z_1, Z_2 - - - - - - - - - Z_{200} T = time in GET seconds X,Y,Z, C.G. location (ft) in body axis orthogonal coordinates with orgin at nav base (reference coordinate A-8)
SET (16,200)	Special event times; data will include special requested event times SET (event, time) Event description in 16 words (max. 160 Hollerith characters) time of event (max. 200 events) in GET seconds (GET from SRB ignition)
REF (27)	REFSMAT data REF1 (3,3) Mean of 1950 to IMU-1 stable member REF2 (3,3) Mean of 1950 to IMU-2 stable member REF3 (3,3) Mean of 1950 to IMU-3 stable member
TRAC (6,100)	Tracker location data, J=1, 100 trackers TRAC (1,J) Station ID number TRAC (2,J) Station geodetic latitude, deg, + north TRAC (3,J) Station geodetic longitude, deg,+ east TRAC (4,J) Station altitude, ft, above mean sea level TRAC (5,J) Station geodetic height, ft, Fischer Earth model TRAC (6,J) Station azimuth, deg, from true north, positive CW

TABLE II.- Continued

(d) Continued

Parameter	Description	
MET (20,1000)	20 meteorological parameters at N points, N maximum of 1000 points	
	MET (1,N)	Geodetic latitude, deg, + north
	MET (2,N)	Longitude, deg + east to 360
	MET (3,N)	Flag; 0 = measured data, 1 = modeled data, 2 = combined measured and modeled data
	MET (4,N)	Spare
	MET (5,N)	Geometric altitude (above mean sea level) in ft
	MET (6,N)	Horizontal wind speed in ft/sec
	MET (7,N)	Direction horizontal wind is coming from relative to true north, north being zero deg, increasing positively clockwise in deg
	MET (8,N)	Ambient temperature in deg R
	MET (9,N)	Ambient pressure in millibars
	MET (10,N)	Ambient density in slugs/ft^3
	MET (11,N)	Dew point in deg R
	[a]MET (12,N)	Ambient temperature systematic uncertainty in deg R
	[a]MET (13,N)	Ambient pressure systematic uncertainty in millibars
	[a]MET (14,N)	Ambient density systematic uncertainty in slugs/ft^3
	[a]MET (15,N)	Horizontal wind speed systematic uncertainty in ft/sec
	[b]MET (16,N)	Horizontal wind speed noise or fluctuation uncertainty in ft/sec
	[b]MET (17,N)	Vertical wind speed noise or fluctuation uncertainty in ft/sec
	[a]MET (18,N)	Horizontal wind direction systematic uncertainty in deg
	[b]MET (19,N)	Horizontal wind direction noise or fluctuation uncertainty in deg

[a]Systematic uncertainty is an estimation 1σ error due to instrument errors, time and space displacement effects, and any other bias-like factors that might contribute to the total low frequency error.

[b]Noise or fluctuation uncertainty is an estimation of the 1σ error due to high frequency atmospheric inhomogeneity such as wind turbulence or gusts.

TABLE II.- Continued

(d) Concluded

Parameter	Description
MET (concluded)	MET (20,N) Spare
KAPPA	Plumbline Earth-fixed flight direction from launch site (Z_E), positive being east of north, deg
PHIO	Geodetic latitude of launch site, positive north of equatorial plane, deg
DELTA	A angle between launch site geocentric radius vector and equatorial plane (declination), deg, positive north of equator.
LAMO	Longitude of launch site, positive east of prime meridian, deg
RSUBO	Geocentric radius of Earth, at launch site, to the vehicle nav base, ft
XSUBO	Geodetic height of the vehicle nav base above the Fischer ellipsoid, ft
NAVO	Structural reference position of nav base (ft) in body axis structure-fixed origin

TABLE II.- Continued

(e) Navigation block output listing format

Flight launch date	OFT number	Navigation block output, ascent (or descent)		
Guidance release time (GMT sec midnight prior launch)				
Center of gravity	GET(sec)	X(FT)	Y(FT)	Z(FT)
	t_1			
	.			
	.			
	.			
	t_n			
Special event times	GET (sec)	Event description		
	t_1 ,			
	.			
	.			
	.			
	t_n ,			
REFSMAT	IMU-1	IMU-2	IMU-3	
	1,1 1,2 1,3			
	2,1 2,2 2,3			
	3,1 3,2 3,3			

Tracker location ID geodetic latitude (deg), longitude (deg), MSLALT (ft), geodetic height (ft), azimuth (deg)

.
.
.
n

Initial launch constants

KAPPA(deg) PHIO(deg) DELTA(deg) LAMO(deg) RSUBO(ft) XSUBO(ft) XNAVO(ft) YNAVO(ft) ZNAVO(ft)

NOTE: The parameter mneumonic and the units are included in this table. If a page change occurs in the midst of a matrix of data, the header titles will be repeated on an attached page.

TABLE II.- Continued

(e) Concluded

Meteorological data

1	GEOD LAT DEG	LON DEG	FLAG	---	GEOM ALT FT	H WIND FPS	H WIND DIR DEG	TEMP DEG R	PRESS MBARS	DENSITY SLG/FT3
2		DEW PT DEG R	TEMP U DEG R	PRESS U MBARS	DENSITY U SLG/FT3	H WIND U SYS FPS	H WIND U NSE FPS	V WIND U NSE FPS	WIND DIR U SYS DEG	WIND DIR U NSE DEG
1										
2										

NOTE: The parameter mneumonic and the units are included in this table. If a page change occurs in the midst of a matrix of data, the header titles will be repeated on an attached page.

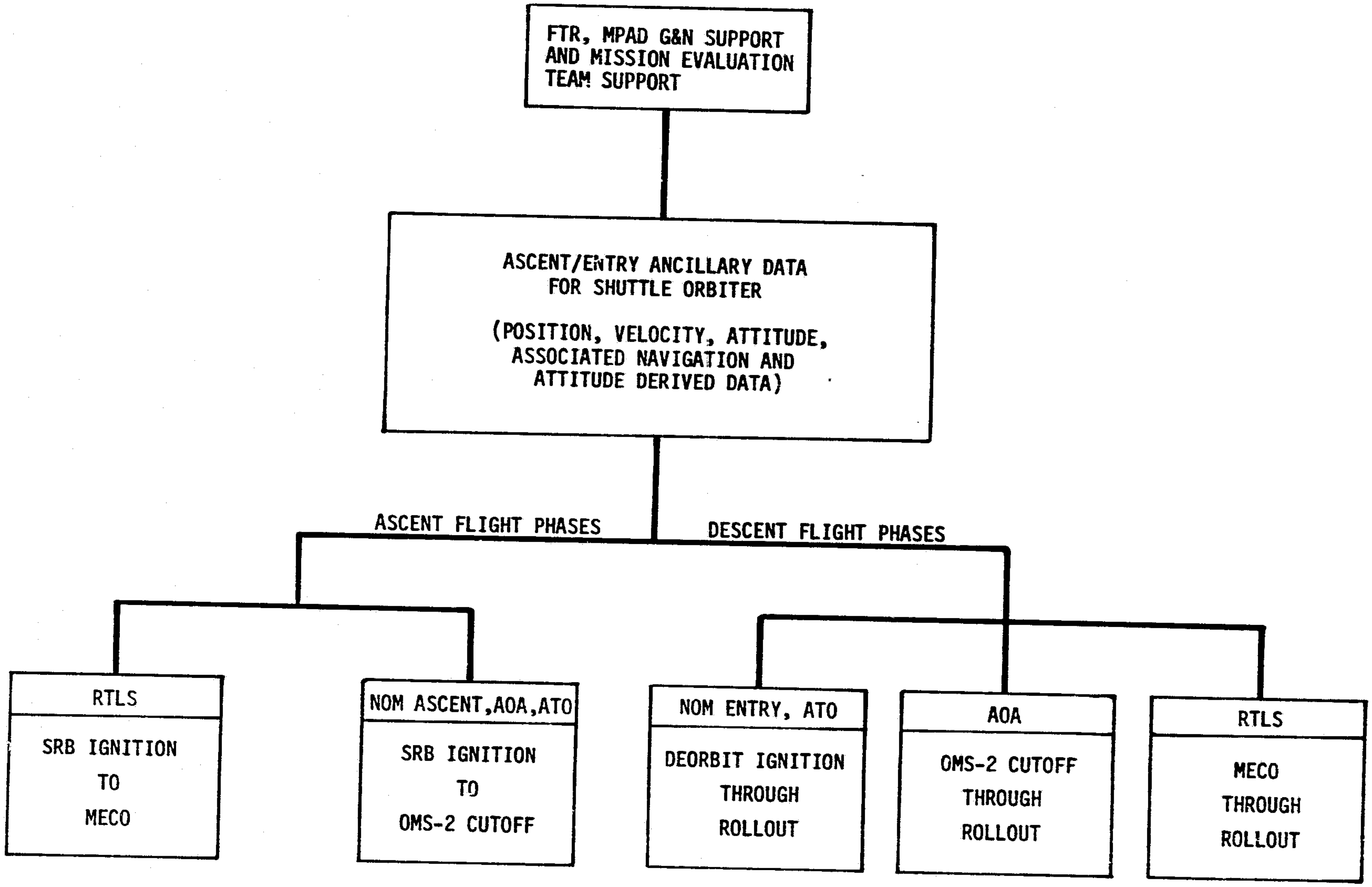


Figure 1.- Ascent/descent ancillary support task.

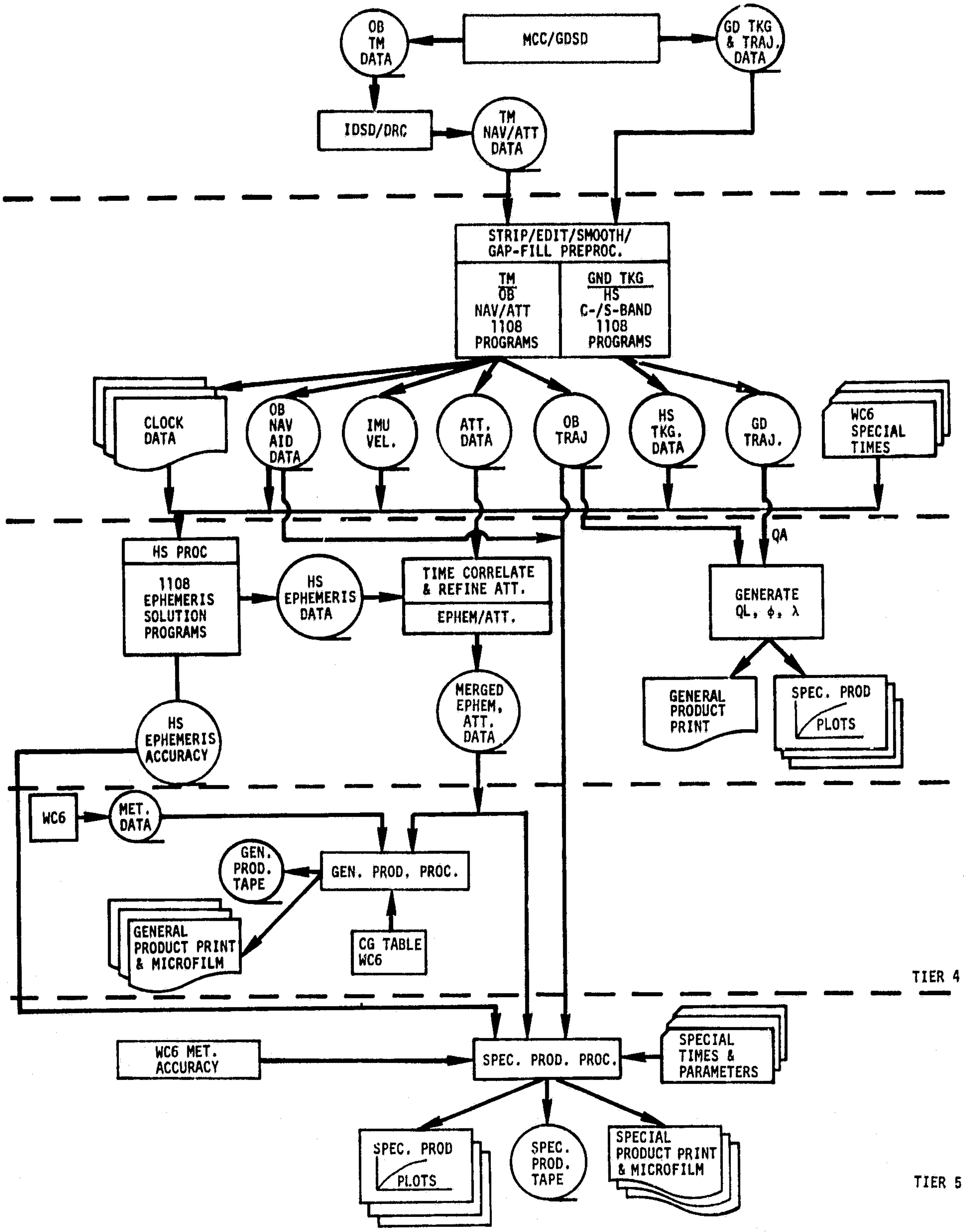


Figure 2.- Data processing functional flow, Orbiter ascent/descent ancillary data (for information).

APPENDIX

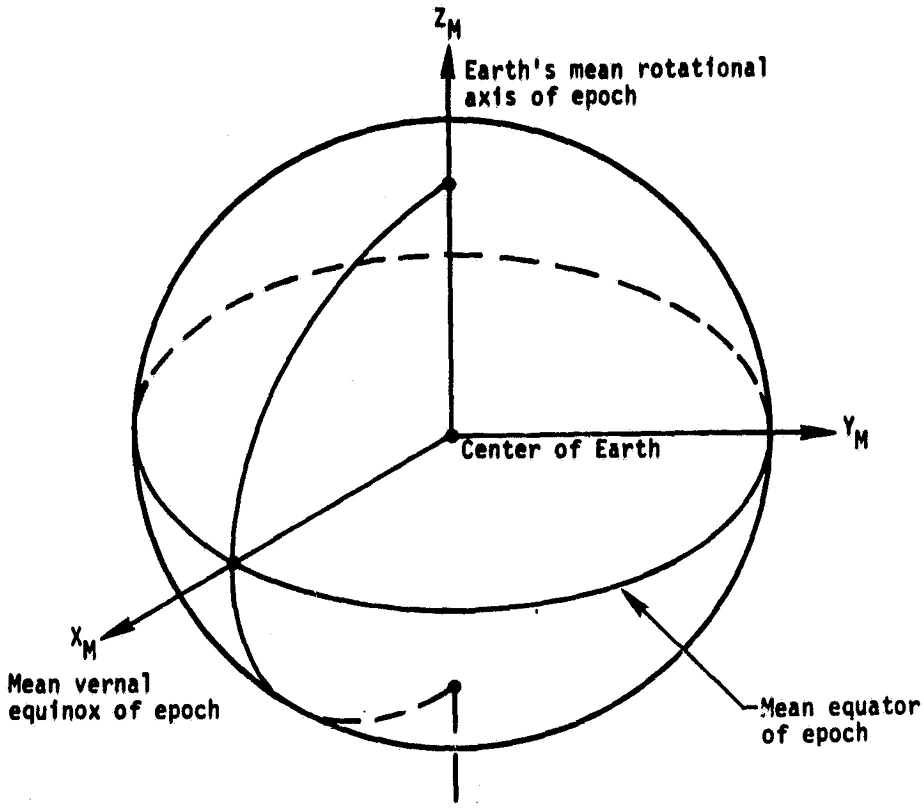
COORDINATE SYSTEM DEFINITIONS AND

OUTPUT PARAMETER EQUATIONS

This appendix contains definitions of the coordinate systems listed in table I(c). The definitions were obtained from reference A-1. In addition to the coordinate systems definitions, equations for selected table I(c) output parameters are given to supplement their tabular descriptions.

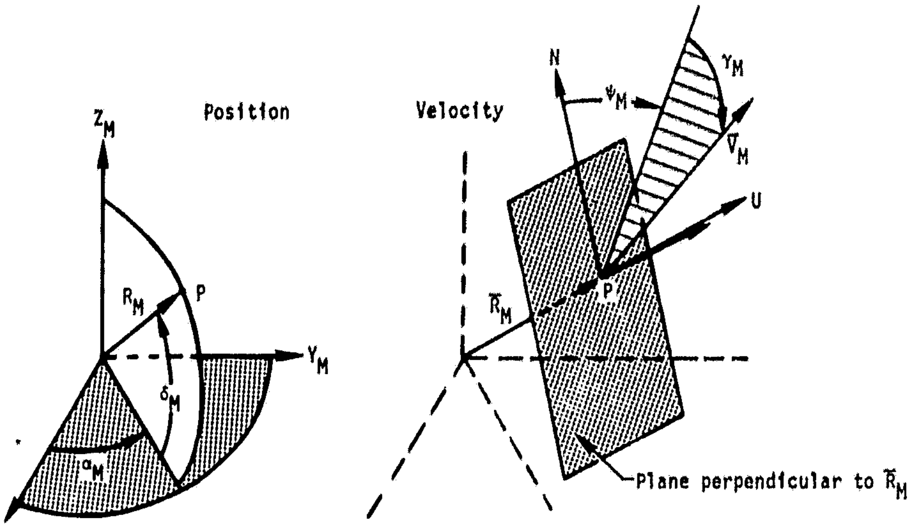
REFERENCE

A-1 Davis, Larry D.: Coordinate Systems for the Space Shuttle Program. NASA TM X-58153, 1974.



NAME:	Aries-mean-of-1950, Cartesian, coordinate system.
ORIGIN:	The center of the Earth.
ORIENTATION:	The epoch is the beginning of Besselian year 1950 or Julian ephemeris date 2433282.423357.
	The X_M-Y_M plane is the mean Earth's equator of epoch.
	The X_M axis is directed towards the mean vernal equinox of epoch.
	The Z_M axis is directed along the Earth's mean rotational axis of epoch and is positive north.
	The Y_M axis completes a right-handed system.
CHARACTERISTICS:	Inertial, right-handed, Cartesian system.

Figure A-1.- Aries-mean-of-1950, Cartesian, coordinate system.



NAME: Aries-mean-of-1950, polar, coordinate system.

ORIGIN: For position - the center of the Earth.
For velocity - the point of interest, $P(X_M, Y_M, Z_M)$.

ORIENTATION AND DEFINITIONS: For position, same as in the Aries-mean-of-1950, Cartesian.
For velocity, reference plane is perpendicular to radius vector $\bar{R}_M$ from center of Earth to point P of interest.

Reference direction is northerly along the meridian containing P.

Polar position coordinates of P are as follows.

α_M, right ascension, is the angle between the projection of the radius vector in the equatorial plane and the vernal equinox of epoch.

δ_M, declination, is the angle between the radius vector and the mean Earth's Equator of epoch.

R_M, magnitude of $\bar{R}_M$.

Polar velocity coordinates of P are as follows.

Let U, E, N denote up, east, and north directions. Then

ψ_M, azimuth, is the angle from north to the projection of $\bar{V}_M$ on the reference plane, positive toward east.

γ_M, flightpath angle, is the angle between the reference plane and $\bar{V}_M$; positive sense toward U.

V_M, magnitude of $\bar{V}_M$ is always positive.

CHARACTERISTICS: Inertial.

Figure A-2.- Aries-mean-of-1950, polar, coordinate system.

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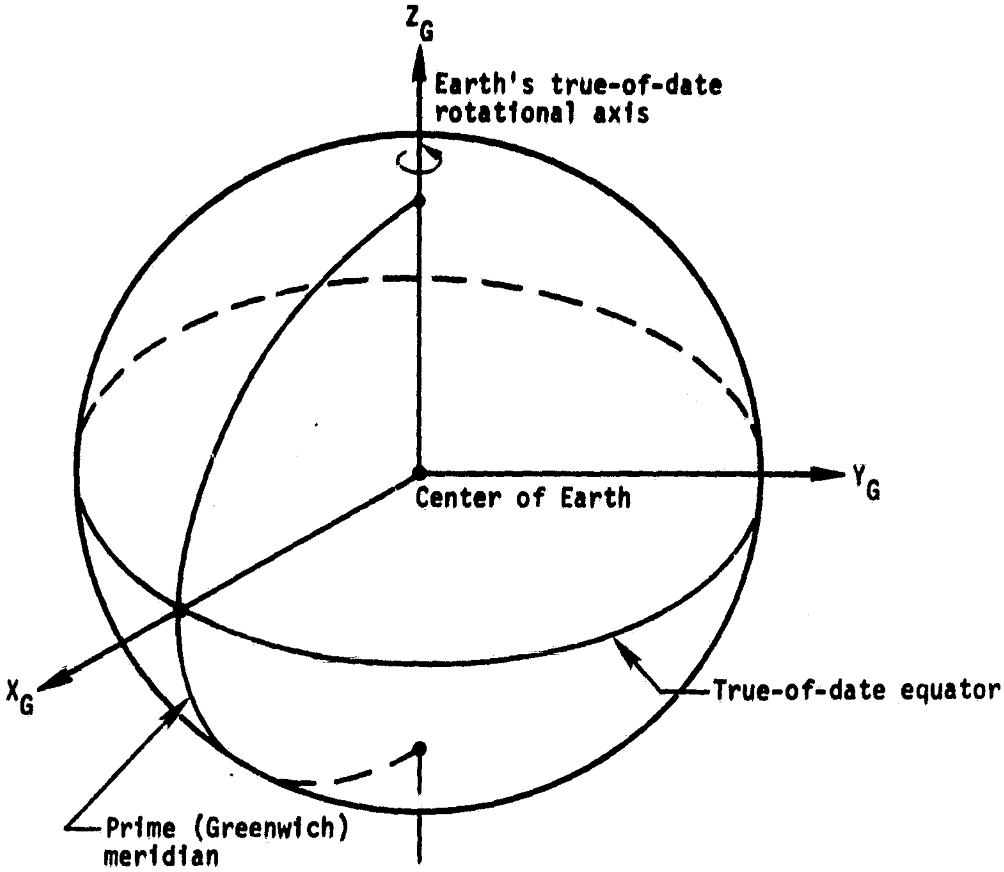
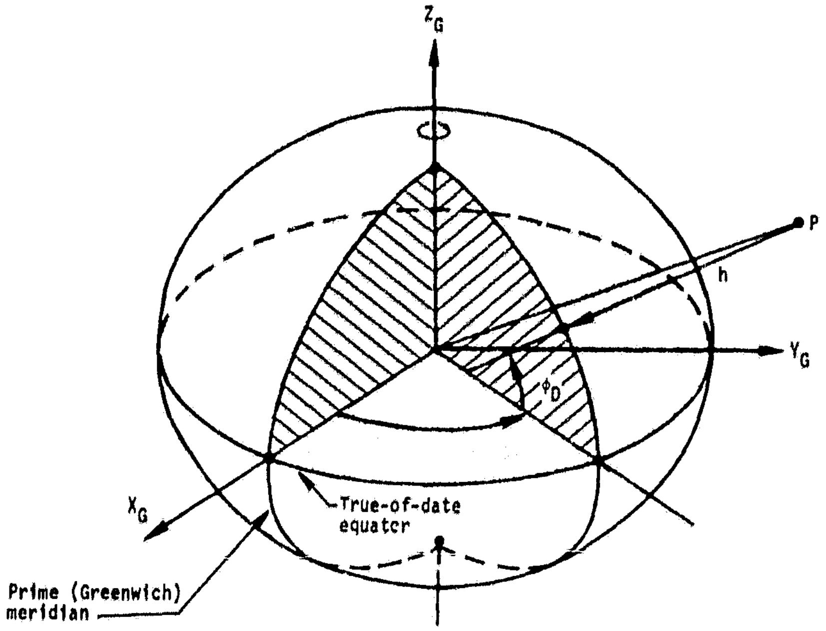


NAME:	Greenwich true of date (geographic) coordinate system.
ORIGIN:	The center of the Earth.
ORIENTATION:	The X_G-Y_G plane is the Earth's true-of-date equator.
	The Z_G axis is directed along the Earth's true-of-date rotational axis and is positive north.
	The $+X_G$ axis is directed toward the prime meridian.
	The Y_G axis completes a right-handed system.
CHARACTERISTICS:	Rotating, right-handed, Cartesian. Velocity vectors expressed in this system are relative to a rotating reference frame fixed to the Earth, whose rotation rates are expressed relative to the Aries-mean-of-1950 system.

Figure A-3.- Greenwich true of date (geographic).



NAME: Geodetic coordinate system.

ORIGIN: This system consists of a set of parameters rather than a coordinate system; therefore, no origin is specified.

ORIENTATION: This system of parameters is based on an ellipsoidal model of the Earth (e.g., the Fischer ellipse of 1960). For any point of interest, we define a line, known as the geodetic local vertical, which is perpendicular to the ellipsoid and contains the point of interest.

h, geodetic altitude, is the distance from the point of interest to the reference ellipsoid, measured along the geodetic local vertical, and is positive for points outside the ellipsoid.

λ is the longitude measured in the plane of the Earth's true equator from the prime (Greenwich) meridian to the local meridian, measured positive eastward.

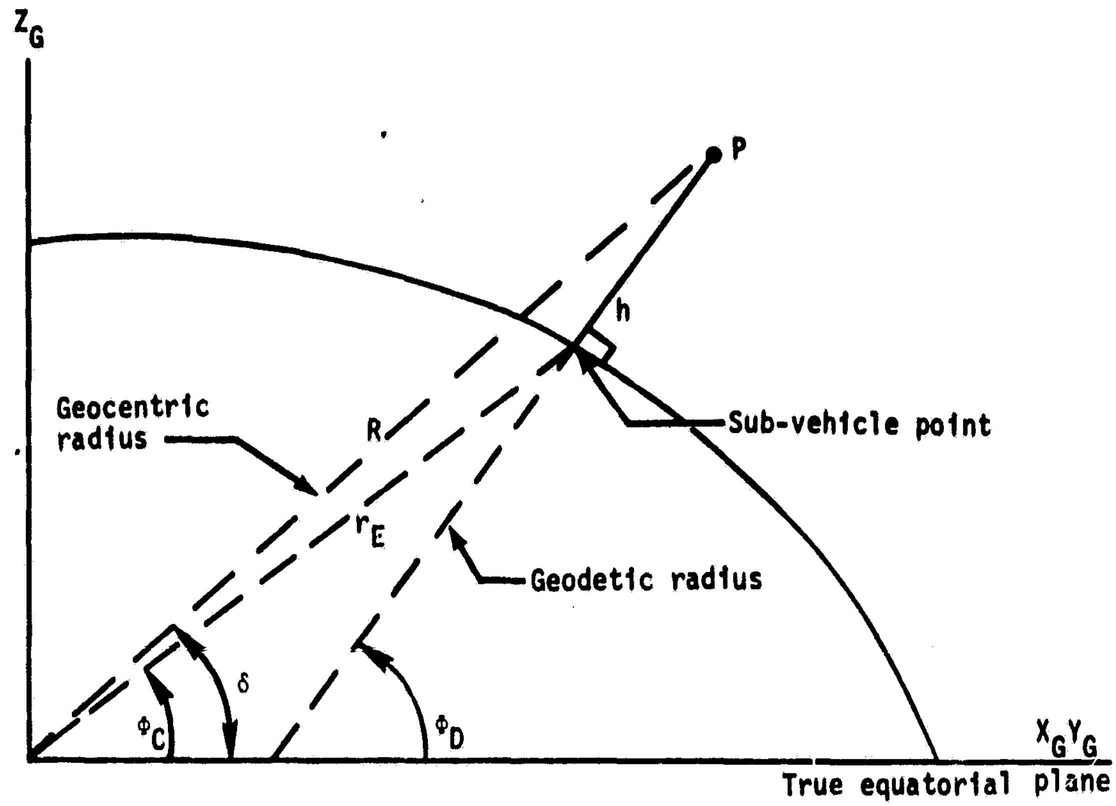
ϕ is the geodetic latitude, measured in the plane of the local meridian from the Earth's true equator to the geodetic local vertical, measured positive north from the equator.

Note: A detailed explanation of declination, geodetic latitude, and geocentric latitude is provided in figure A-4(b).

CHARACTERISTICS: Rotating polar coordinate parameters. Only position vectors are expressed in this coordinate system. Velocity vectors should be expressed in the Aries-mean-of-1950, or the Aries true-of-date, polar for inertial or quasi-inertial representations, respectively. The Fischer ellipsoid model should be used with this system.

(a) Basic definitions.

Figure A-4.- Geodetic.



NAME: Geodetic coordinate system of point P.

DEFINITIONS: h is the altitude of point P measured perpendicular from the surface of the referenced ellipsoid.

ϕ_D is the geodetic latitude of point P (angle between the true equatorial plane and the geodetic radius of point P).

ϕ_C is the geocentric latitude of point P (angle between the true equatorial plane and the geocentric radius vector to the sub-vehicle point of point P).

δ is the angle between the geocentric radius vector to point P and the equatorial plane (declination).

λ is the longitude of point P angle (+ east) between the plane of the figure and the plane formed by the Greenwich meridian.

(b) Detailed explanation.

Figure A-4.- Continued.

Let Z_{EF} be the Earth's north polar axis and X_{EF} pass through the Greenwich meridian. Let

R_E = Earth's equatorial radius

R_p = Earth's polar radius

e = $(R_E-R_p)/R_E$ = ellipticity or flattening

To calculate geodetic north latitude, ϕ, east longitude, λ, and altitude above the ellipsoid H, set $B = 0.0067$ and iterate five times.

$$B = \frac{e(2-e)R_E}{\sqrt{(X_{EF}^2 + Y_{EF}^2)/(B+1)^2 + (1-e)^2 Z_{EF}^2}}$$

Then

$$\phi = \arctan \frac{Z_{EF}}{\sqrt{X_{EF}^2 + Y_{EF}^2 \ /(B+1)^2}}$$

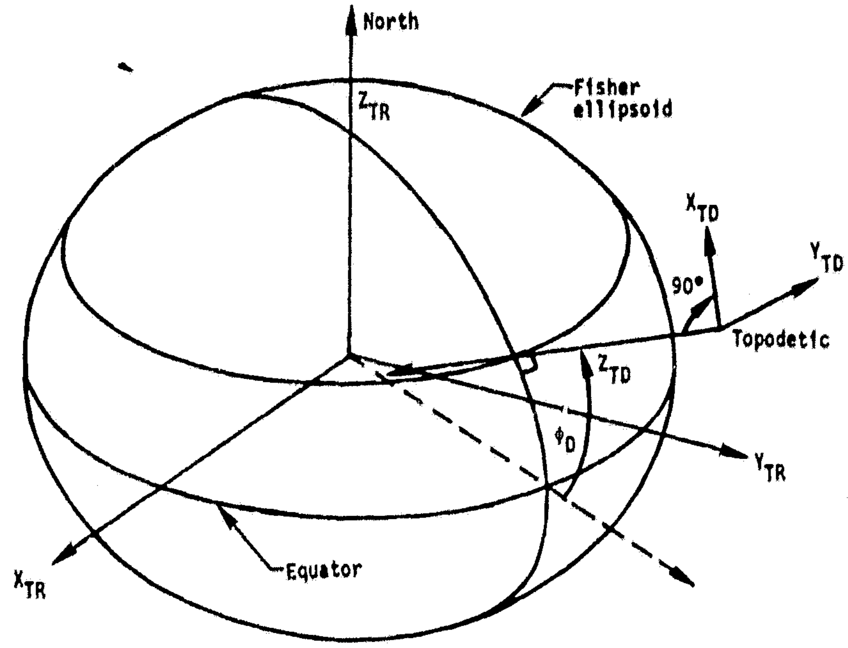
$$\lambda = \arctan\,(Y_{EF}/X_{EF})$$

$$H = \left(1 - B\,\frac{(1-e)^2}{e(2-e)}\right) \sqrt{(X_{EF}^2 + Y_{EF}^2)/(B+1)^2 + Z_{EF}^2}$$

where X_{EF}, Y_{EF}, and Z_{EF} are Greenwich true-of-date (A-3) values.

(c) Definitions of ϕ, λ, H.

Figure A-4.- Concluded.



NAME: Topodetic coordinate system.

ORIGIN: Orbiter center of mass[a] or navigation base.

ORIENTATION: Z_{TD} is normal to a geodetic local tangent plane and is positive toward the Earth's center.

X_{TD} is perpendicular to Z_{TD} axis and is positive northward along the meridian plane containing the Orbiter.

Y_{TD} completes the right-handed orthogonal system.

CHARACTERISTICS: Rotating, right-handed, Cartesian system. Velocity vectors are expressible in this system for the Orbiter, given relative velocity V_{TD} in this system.

$$V_{TD} = (\dot{X}_{TD}^2 + \dot{Y}_{TD}2 + \dot{Z}_{TD}2)^{1/2} = \text{magnitude of } \bar{V}_{TD}$$

$$\gamma_{TD} = \sin^{-1}\left(\frac{-\dot{Z}_{TD}}{V_{TD}}\right) = \text{flightpath angle (relative)}$$

$$\psi_{TD} = \tan^{-1}\left(\frac{\dot{Y}_{TD}}{\dot{X}_{TD}}\right) = \text{azimuth angle (relative)}$$

ϕ_D = geodetic latitude

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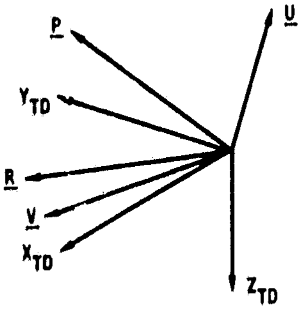
[a]A similar system may be defined for any point of interest.

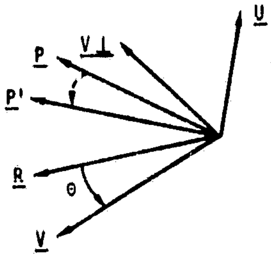
Figure A-5.- Topodetic.

The bank angle, or angle of roll about the relative wind vector is computed in the topodetic system. To define the bank angle $\underline{R}$, $\underline{P}$, and $\underline{V}$ are first defined respectively as unit vectors along the roll axis, pitch axis, and wind-relative velocity vector.

Further, define $\underline{U}=\underline{R}\times\underline{V}=(\ell,m,n)^T$ and ℓ, m, and n are directed cosines of $\underline{U}$ in the topodetic system.



Rotating $\underline{R}$ into $\underline{V}$, in the plane of $\underline{R}$ and $\underline{V}$, defines θ, and is accomplished with matrix M $(\underline{U}, \theta)$, also $\underline{P}'$ is formed by the rotation



$$\theta = \cos^{-1}\left(\underline{R} \cdot \underline{V}\right)$$

$$M\,(U,\theta) = \begin{bmatrix} \left(\ell^2 + (1-\ell^2)\cos\theta\right) & \left(\ell m(1-\cos\theta)-n\sin\theta\right) & \left(\ell n(1-\cos\theta)+m\sin\theta\right) \\ \left(\ell m(1-\cos\theta)+n\sin\theta\right) & \left(m^2+(1-m^2)\cos\theta\right) & \left(mn(1-\cos\theta)-\ell\sin\theta\right) \\ \left(\ell n(1-\cos\theta)-m\sin\theta\right) & \left(nm(1-\cos\theta)+\ell\sin\theta\right) & \left(n^2+(1-n^2)\cos\theta\right) \end{bmatrix}$$

$$\underline{P}' = M\,(\underline{U},\theta)\,\underline{P}$$

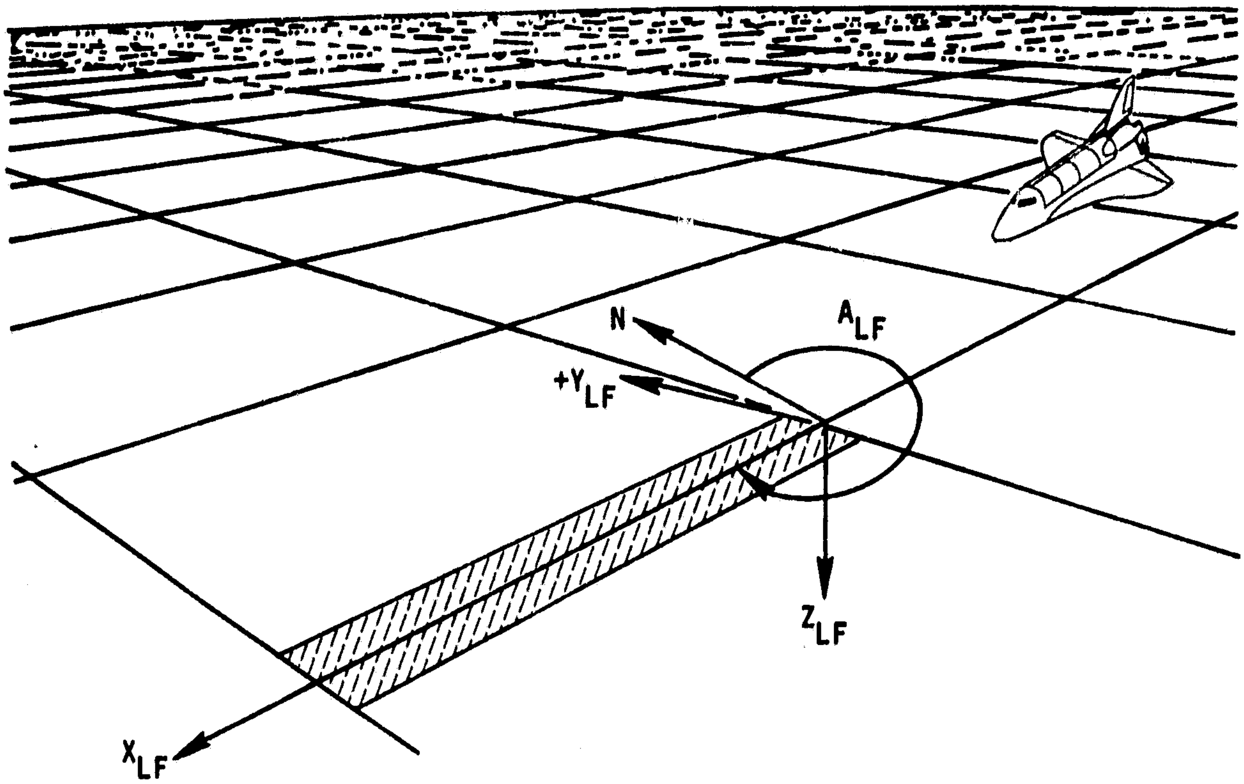
and $\underline{V\perp}$ is a vector in the X-Y plane orthogonal to $\underline{V}$ and is defined as $\underline{V\perp} = \underline{Z}_{TD} \times \underline{V} \,/\, |\underline{Z}_{TD} \times \underline{V}|$

Finally, bank angle is the angle between $\underline{P}'$ and $\underline{V\perp}$

$$\text{Bank Angle} = \cos^{-1}\left(\underline{P}' \cdot \underline{V\perp} \,/\, |\underline{V\perp}|\right)$$

and is positive when right wing is below the horizontal.

Figure A-5.- Concluded.



NAME:	Landing field coordinate system.
ORIGIN:	Runway center at approach threshold.
ORIENTATION AND DEFINITIONS:	Z_{LF} axis is normal to the ellipsoid model through the runway centerline at the approach threshold and positive toward the center of the Earth.
	X_{LF} axis is perpendicular to the Z_{LF} axis and lies in a plane containing the Z_{LF} axis and the runway centerline (positive in the direction of landing).
	Y_{LF} axis completes the right-handed system.
	A_{LF} is the runway azimuth measured in the $X_{LF}Y_{LF}$ plane from true north to the $+X_{LF}$ axis (positive clockwise).
CHARACTERISTICS:	Rotating, Earth-referenced.

Figure A-6.- Landing field.

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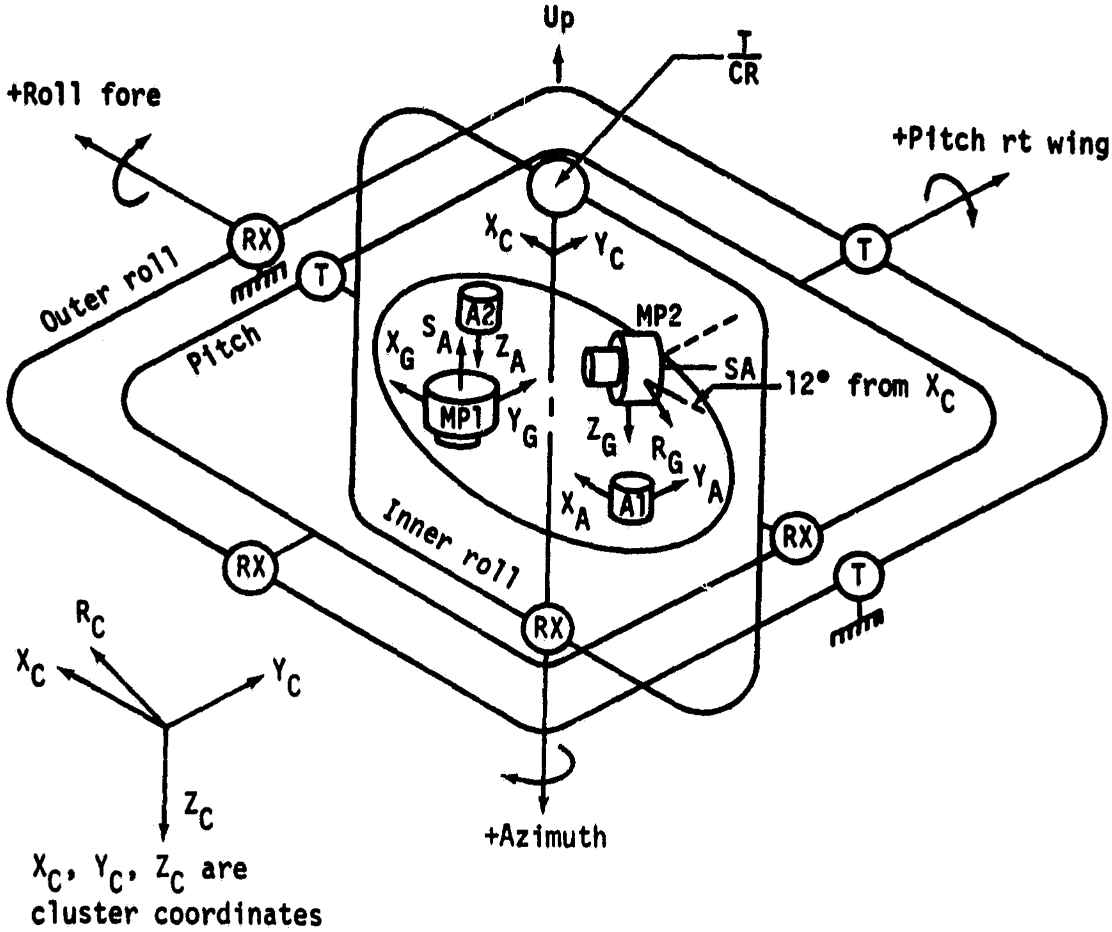


Note: X_G = X gyro I.A. ⎫ Vertical gyro
Y_G = Y gyro I.A. ⎭

Z_G = Z gyro I.A. ⎫ Azimuth gyro
R_G = Red gyro I.A. ⎭

Z_A = Z accel. sens. axis } Single axis accel.

X_A = X accel. sens. axis ⎫ Dual axis accel.
Y_A = Y accel. sens. axis ⎭

T = Gimbal torquer

RX = Gimbal angle resolver

Figure A-7.- IMU stable member.

NAME: Stable Member (IMU)

ORIGIN: The intersection of the innermost gimbal axis and the measurement plane of the XY two axis accelerometer.

ORIENTATION: The Z_C axis is coincident with the innermost gimbal axis.

The X_C axis is determined by the projection of the X accelerometer input axis (IA) onto a plane orthogonal to Z_C. Y_C completes a right-handed triad.

In a perfect IMU, with all misalinements zero, these relationships hold:

The X accelerometer and X gyro IAS are parallel to the X_1 axis.
The Y accelerometer and Y gyro IAS are parallel to the Y_1 axis.
The Z accelerometer and Z gyro IAS are parallel to the Z_1 axis.

CHARACTERISTICS: Nonrotating, right-handed, Cartesian system.

The reference alinement for the gimbal case shall be defined with the four gimbal angles at zero and with the vehicle in a horizontal position. In a perfect IMU, with all misalinements zero and with all gimbal angles at zero, the following relationships hold.

The outer roll axis and the X_C axis will be parallel to X_{NB}. Positive X_C will be in the forward direction. Positive roll gimbal angles will be in the sense of a right-handed rotation of the gimbal case relative to the platform about the plus outer roll axis.

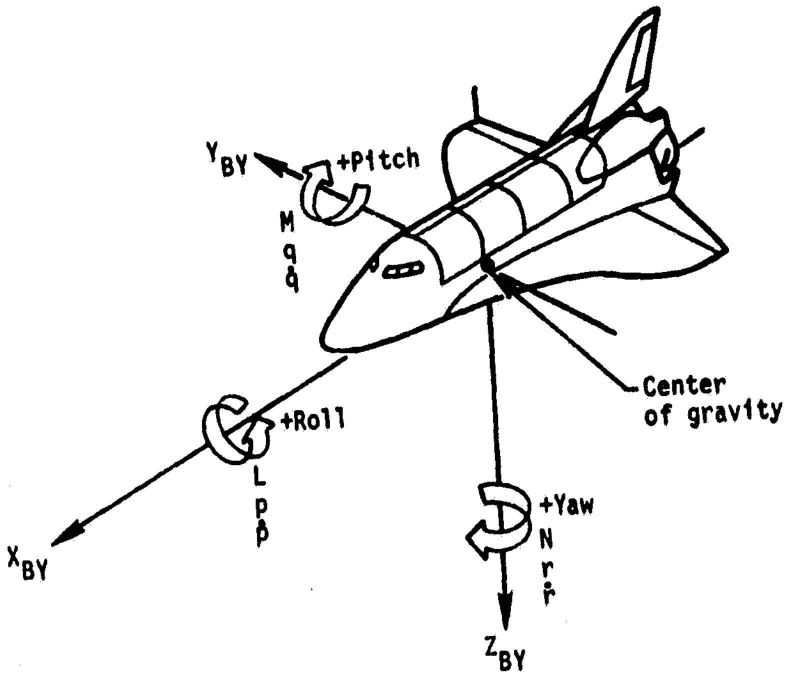
The pitch axis and Y_C will be parallel to Y_{NB}. Positive Y_C will be to the right of an observer looking forward in the vehicle. Positive pitch gimbal angles will be in the sense of a right-handed rotation of the gimbal case relative to the platform about the plus pitch axis.

The inner roll axis will be parallel to the outer roll axis, with the sense of rotation the same as for the outer roll axis.

The aximuth axis and Z_C will be parallel to Z_{NB}. Positive Z_C will be down relative to an observer standing in the vehicle. Positive azimuth gimbal angles will be in the sense of a right-handed rotation of the gimbal case relative to the platform about the plus azimuth axis.

X_{NB}, Y_{NB}, Z_{NB} are Cartesian components of the navigation base coordinate system.

Figure A-7.- Concluded.



NAME: Body axis coordinate system.

ORIGIN: Orbiter center of mass or navigation base.

ORIENTATION: X_{BY} axis is parallel to the Orbiter structural body X_O axis; positive toward the nose.

Z_{BY} axis is parallel to the Orbiter plane of symmetry and is perpendicular to X_{BY}, positive down with respect to the Orbiter fuselage.

Y_{BY} axis completes the right-handed orthogonal system.

CHARACTERISTICS: Rotating, right-handed, Cartesian system.

L, M, N: Moments about X_{BY}, Y_{BY}, and Z_{BY} axes, respectively.

p, q, r: Body rates about X_{BY}, Y_{BY}, and Z_{BY} axes, respectively.

$\dot{p}$, $\dot{q}$, $\dot{r}$: Angular body acceleration about X_{BY}, Y_{BY}, and Z_{BY} axes, respectively.

The Euler sequence that is commonly associated with this system is a pitch, yaw, roll sequence, where θ = pitch, Ψ = yaw, and ϕ = roll. This attitude sequence is pitch, yaw, and roll around the Y_{BY}, Z_{BY}, and X_{BY} axes, respectively.

(a) Basic definition.

Figure A-8.- Body axes.

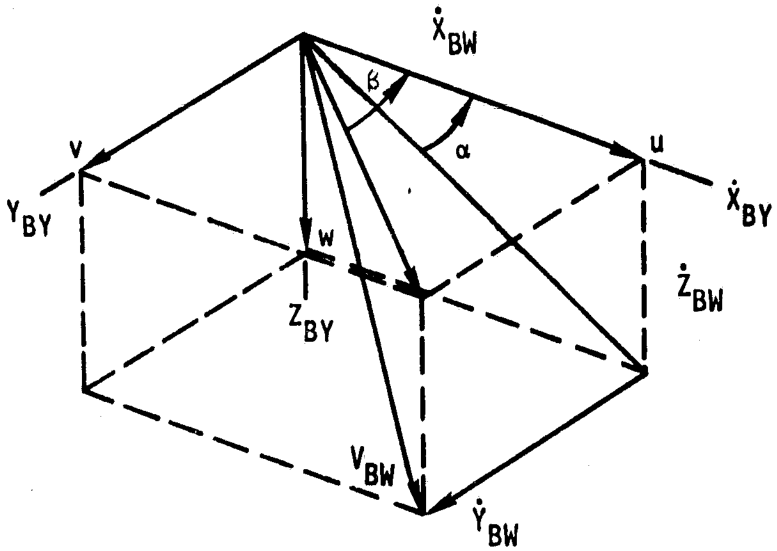
The wind-relative velocity vector, $\overline{V}_{BW}$, expressed in the body-axis system, shall be used to define the angle of attack, α, and the sideslip angle, β, as follows:

$$\alpha = \tan^{-1}\left(\frac{\dot{z}_{BW}}{\dot{x}_{BW}}\right)$$

$$\beta = \tan^{-1}\left(\frac{\dot{y}_{BW}}{\dot{x}_{BW}}\right)$$

where $\dot{x}_{BW}$, $\dot{y}_{BW}$, $\dot{z}_{BW}$ are the components of $\overline{V}_{BW}$ in the body-axis system (fig. A-8(b)).

Note: $\overline{V}_{BW}$ is air-relative velocity; i.e., wind effects are included.



(b) Resolution of wind-relative velocity along vehicle body axes.

Figure A-8.- Concluded.

Earth surface range, S, shall be defined as the product of (1) the magnitude of the Earth-fixed position vector to the launch or landing site and (2) the central angle between the site vector and the Earth-fixed position vector to the Orbiter; i.e.,

$$S = |\overline{R}_{SITE}|\ \theta_E$$

where $\theta_E = \cos^{-1} \dfrac{\overline{R}_{SITE} \cdot \overline{R}_{ORB}}{|\overline{R}_{SITE}|\ |\overline{R}_{ORB}|}$ = central angle

$\overline{R}_{SITE}$ = Earth-fixed position vector to launch pad (ascent) or to runway coordinate system origin (descent)

$\overline{R}_{ORB}$ = Earth-fixed position vector to Orbiter

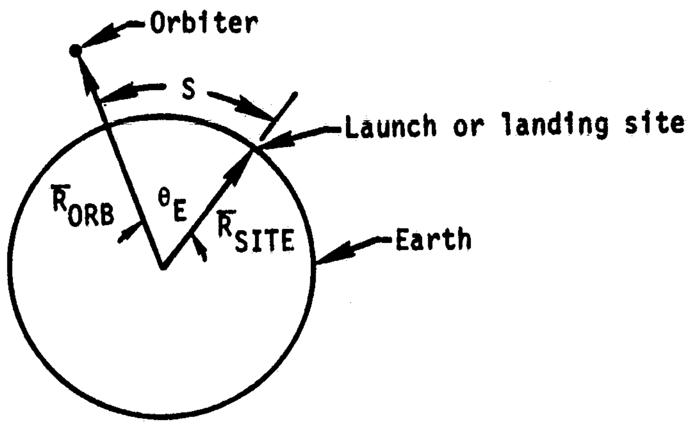


Figure A-9.- Definition of Earth surface range.

Dynamic pressure $\bar{q}$ shall be defined as

$$\bar{q} = 1/2\, \rho\, VTD^2$$

and Mach number M shall be defined as

$$M = \frac{VTD}{a}$$

where VTD = magnitude of wind-relative velocity

ρ = atmospheric density

a = speed of sound

Figure A-10.- Definition of dynamic pressure and Mach number.

$$T' = 726.97 + 0.468T_\infty + 3.4098447 \times 10^{-6} V_\infty^2 \qquad (^\circ K)$$

T_∞ in $^\circ K \rightarrow$ from flightpath atmosphere

V_∞ in fps $\rightarrow$ wind-relative (true) airspeed = VTD

$$C_\infty' = \left(\frac{T'}{T_\infty}\right)^{.5} \left[\frac{T_\infty + 122.1 \times 10^{-(5/T_\infty)}}{T' + 122.1 \times 10^{-(5/T')}}\right] \qquad (N/D)$$

$$\mu = \frac{3.0449939 \times 10^{-8} T_\infty^{1.5}}{(T_\infty + 110.4)} \qquad (lbf\text{-}sec/ft^2)$$

$$Re_\infty L_B = \frac{VTD \rho L_B}{\mu} \qquad (N/D)$$

ρ in slug/ft$^3 \rightarrow$ from flightpath atmosphere

L_B = body length = 107.5 ft

$$M_\infty = \frac{VTD}{a} = \frac{VTD}{\sqrt{RT_\infty}} = \frac{VTD}{\sqrt{4289.05T_\infty}} \qquad (N/D)$$

$$\bar{V}_\infty' = M_\infty \sqrt{\frac{C_\infty'}{Re_\infty L_B}} \qquad (N/D)$$

Figure A-11.- Hypersonic viscous parameter.

Drag over mass (D/M) is calculated as follows:

$$D/M = \frac{\Delta \bar{V}_S}{\Delta t} \cdot \frac{\bar{V}_{REL}}{|\bar{V}_{REL}|}$$

where $\bar{V}_{REL}$ is the wind-relative velocity vector

$= \bar{V}_{inertial} - \omega X \bar{R}_{inertial}$

and ω is the Earth rotation rate

$\bar{R}_{inertial}$ = Mean of 50 position vector

$\bar{V}_{inertial}$ = wind-relative Mean of 50 velocity vector

$|V_{REL}|$ = magnitude of the wind-relative vector

ΔV_S = sensed change in velocity

Δt = time interval over which ΔV_S is determined

$$ACC\_LIFT = \frac{\Delta \bar{V}_S}{\Delta t} \cdot \frac{[\bar{Y}\_BD\_UNIT \ X \ \bar{V}_{REL}]}{|\bar{Y}\_BD\_UNIT \ X \ \bar{V}_{REL}|}$$

$\bar{Y}$_BD_UNIT is unit vector passing through Y body (right wing). It is the second column of the transformation matrix body to M50.

LOD = ACC_LIFT/(D/M)

LOD = lift over drag

$$LOAD\_TOTAL = \left|\frac{\Delta \bar{V}_S}{\Delta t}\right| / 32.174$$

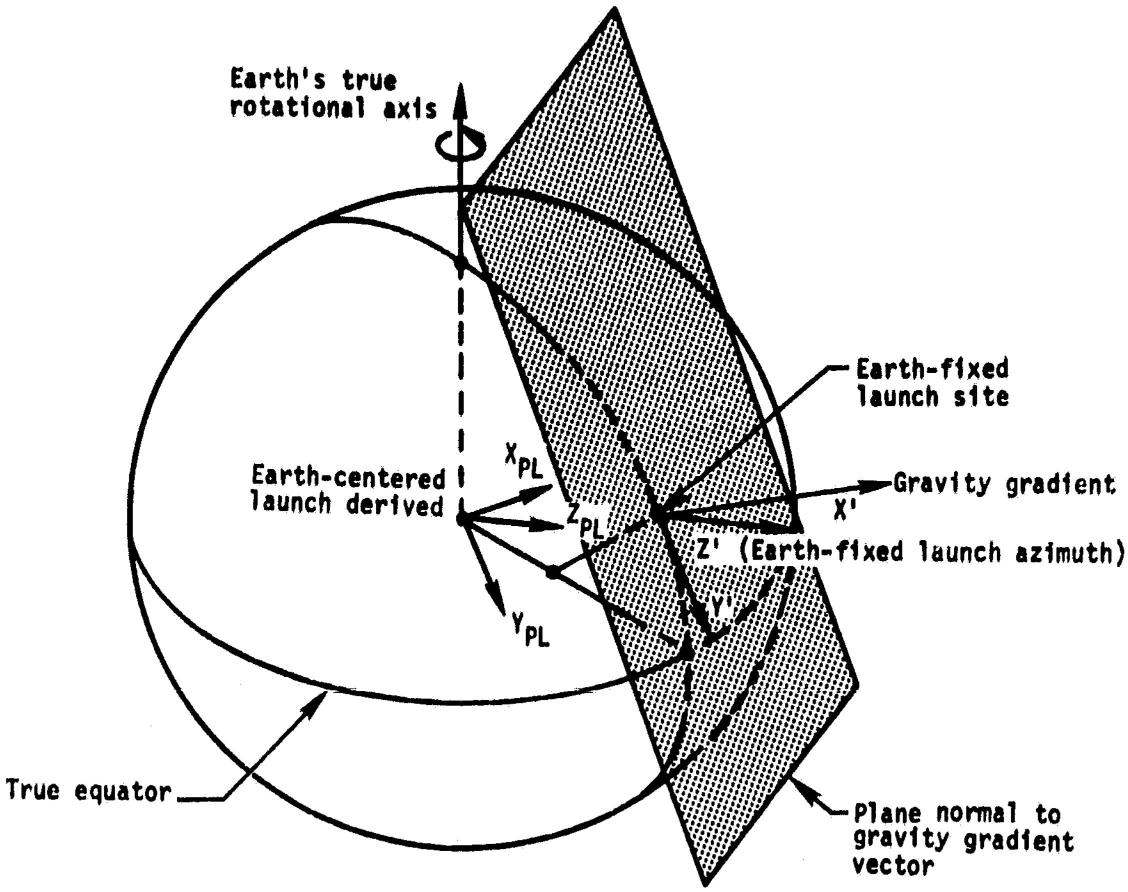
Load total is total load factor. It is total acceleration expressed in g's of 32.174 fps^2.

Equivalent airspeed (EAS) = $17.1865 \sqrt{1/2 \ \rho \ V_e^2}$ knots

ρ = atmospheric density in slug/ft^3

V_e = wind-relative speed in fps

Figure A-12.- Calculations for drag acceleration, lift of drag, total load factor, and equivalent airspeed.



NAME: Plumbline coordinate system.

ORIGIN: At the center of the Earth.

ORIENTATION AND DIRECTIONS: The X_{PL} axis is parallel to the gravity gradient X', which passes through the launch site and is positive toward the launch site. The X_{PL} axis is fixed at SRB ignition.

The Z_{PL} axis is parallel to and positive in the same direction as the chosen Earth-fixed launch azimuth direction Z'.

The Y_{PL} axis is parallel to the Y' and completes a standard right-handed system.

The Y_{PL}-Z_{PL} plane is normal to the launch site gravity gradient vector.

CHARACTERISTICS: Inertial, right-handed, Cartesian.

Figure A-13.- Plumbline.

ORIGINAL PAGE IS OF POOR QUALITY

Equations (1), (2), and (3) calculate the acceleration due to gravity using the eight harmonic gravity equations.

$$AG_X = -\mu \left(\rho_x \frac{\alpha^4}{\rho_4} - \frac{\rho_z \ \rho_x}{\alpha^2 \rho} X - \frac{\rho_x}{\alpha\rho} Z - \frac{\rho_y}{\alpha\rho} Y \right) \text{ in fps}^2 \quad (1)$$

$$AG_Y = -\mu \left(\rho_y \frac{\alpha^4}{\rho^4} - \frac{\rho_z \ \rho_y}{\alpha^2 \rho} X - \frac{\rho_y}{\alpha\rho} Z - \frac{\rho_x}{\alpha\rho} Y \right) \text{ in fps}^2 \quad (2)$$

$$AG_Z = -\mu \left(\rho_z \frac{\alpha^4}{\rho^4} + \frac{\rho_x{}^2 \ \rho_y{}^2}{\rho^2 \alpha} X - \frac{\rho_z}{\alpha^2} Z \right) \text{ in fps}^2 \quad (3)$$

where

$\mu = 1.40764544 \times 10^{16}$ in $\frac{\text{lb ft}^2}{\text{sec}}$ = gravitational mass, which is the product of gravitational constant and Earth mass.

ρ_x, ρ_y, ρ_z, are the total position coordinates in ft

Initially, the total position value at $t-1 = 0$ is

ρ initial = ECI location of launch pad

Subsequent first estimates of total position values needed to calculate gravitational acceleration is

$$\rho_t = \rho_{t-1} + \left(\frac{VS_t + VS_{t-1}}{2} + VG_{t-1} \right) dt + \frac{AG_{t-1}}{2} dt^2 \text{ in ft} \quad (4)$$

where

Figure A-14.- Gravitational acceleration computation.

VS = sensed velocity in fps

VG = velocity due to gravity in fps

(VG_{t-1} set = 0 at t-1 = 0)

AG = acceleration due to gravity in fps^2

(AG_{t-1} set = 0 at t-1 = 0)

dt = time interval in seconds

$\rho = \sqrt{\rho_x{}^2 + \rho_y{}^2 + \rho_z{}^2}$ in ft

α = 20925639.8 in ft = radius of Earth

and

$$X = \sum_{\ell=2}^{8} FJ(\ell) \frac{\alpha^{\ell+2}}{\rho^{\ell+2}} \left(\frac{\rho_z}{\alpha} PNP_{\ell-1} + \ell X_{\ell-1} \right) \tag{5}$$

$$+ \frac{\rho_z}{\rho} \sum_{m=1}^{8} \Bigg[(2m-1) PMM_m \left(c(mm)\cos\lambda + s(mm)\sin\lambda \right) m \frac{\alpha^{m+2}}{\rho^{m+2}}$$

$$- \sum_{n=m+1}^{8} \frac{\alpha^{n+2}}{\rho^{n+2}} \left(c(nm)\cos\lambda + s(nm)\sin\lambda \right) \left(-nP_n \frac{\rho_z}{\alpha} + P_{n-1}\ (n+m) \right) \Bigg]$$

$$Y = \sum_{m=1}^{8} - \Bigg[(zm^2 - m) \frac{\alpha^{m+2}}{\rho^{m+2}} PMM_m \left(c(mm)\sin\lambda - s(mm)\cos\lambda \right) \tag{6}$$

$$+ m \sum_{n=m+1}^{8} \left(2 \frac{\rho_z}{\alpha} (n-1) P_{n-1} - \frac{(n+m-1)}{(n-m)} Pn{-}2 \right)$$

$$\left(C(nm)\sin\lambda - s(nm)\cos\lambda \right) \frac{\alpha^{n÷2}}{\rho^{n+2}} \Bigg]$$

Figure A-14.- Continued.

$$Z = \sum_{\ell=2}^{8} \frac{(\ell+1)}{\ell} FJ(\ell) \frac{\alpha^{\ell+2}}{\rho^{\ell+2}} \left(\frac{\rho_z}{\alpha} PNP_{\ell-1} + \ell X_{\ell-1}\right) \tag{7}$$

$$\left((2\ell-1) \frac{\rho_z}{\alpha} X_{\ell-1} - (\ell-1) X_{\ell-2}\right) -$$

$$\sqrt{-\frac{\rho_x{}^2 + \rho_y{}^2}{\rho}} \sum_{m=1}^{8} \left[(2m^2+m-1) \frac{\alpha^{m+2}}{\rho^{m+2}} \left(c(mm)\cos\lambda + s(mm)\sin\lambda\right)\right.$$

$$+ \sum_{n=m+1}^{8} (n-1) \frac{\alpha^{n+2}}{\rho^{n+2}} \left(2 \frac{\rho}{\alpha} \quad (n-1)\ P_{n-1} - \frac{(n+m-1)}{(n-m)} P_{n-2}\right)$$

$$\left.\left(\cos\lambda\ c(nm) + \sin\lambda\ s(nm)\right)\right]$$

where the values for the zonal, sectoral and tesseral harmonic coefficients, FJ, C_{nm} and S_{nm} respectively, are presented in figure A-16.

Coefficient selection is accomplished by:

$$C(mm)_m = C\left(1 + \sum_{i=2}^{m} 10-m\right) \text{ for } m>1,\ C(mm)_1 = C(1) \tag{8}$$

$$C(nm)_{nm} = C\left(\sum_{i=2}^{m} 10-m + n-m\right) \text{ for } m>1, \text{ else } C(nm)nm = C(n) \tag{9}$$

$$S(mm)_m = S\left(1 + \sum_{i=2}^{m} 10-m\right) \text{ for } m>1,\ S(mm)_1 = S(1) \tag{10}$$

$$S(nm)_{nm} = S\left(\sum_{i=2}^{m} 10 - m + n-m\right) \text{ for } m>1, \text{ else } S(nm)_{nm} = S(n) \tag{11}$$

and

Figure A-14.- Continued.

$$PNP_{\ell} = \frac{\rho_z}{\alpha} PNP_{\ell-1} + \ell(PN_{\ell}),\ PNP_1 = \frac{\rho_z}{\alpha} + 1 \tag{12}$$

$$PMM_m = (2m-1) \frac{\rho_x{}^2+\rho_y{}^2}{\rho} PMM_{m-1},\ PMM_o = 1 \tag{13}$$

$$\lambda = -\omega * T + \tan^{-1}\left(\rho_x/\rho_y\right) \text{ in radians = latitude} \tag{14}$$

$$P_n = \frac{P_{n-1} \dfrac{\rho_z}{\alpha} (2n-1) - P_{n-2}\ (n-1)}{(n-m)},\ P_o = XP,\ P_1 = 0 \tag{15}$$

$$PN_{\ell} = PN_{\ell-1} \frac{\rho_z}{\alpha} (2\ell-1) - PN_{\ell-2}(\ell-1),\ PN_o = 1,\ PN_1 = \frac{\rho_z}{\alpha} \tag{16}$$

$$XP = \sum_{n=1}^{8} \frac{XP_{n-1} \dfrac{\rho_z}{\alpha} (2n-1) - XP_{n-2}\ (n-1)}{n},\ XP_o = 1,\ XP_1 = \frac{\rho_z}{\alpha} \tag{17}$$

where

T = time in seconds from epoch

ω = 0.00007292115147 in radians/sec = rotation rate of Earth

Figure A-14.- Concluded.

The following equations describe the method of calculating the total position and velocity.

Total position (ρ) at time t is defined as the integral of the total velocity from the initial time to time t. Equation (18) adds the total position at time $t-1$ with the change in position from time $t-1$ to t.

$$\rho_t = \rho_{t-1} + \left(\frac{VS_t + VS_{t-1} + VG_t + VG_{t-1}}{2}\right) dt \quad \text{in ft} \tag{18}$$

where

ρ = total position in ft

VS = sensed velocity in fps (input data)

VG = velocity due to gravity in fps

dt = time interval in sec

and

$$VG_t = VG_{t-1} + \left(\frac{AG_t + AG_{t-1}}{2}\right) dt \quad \text{in fps} \tag{19}$$

where

AG = acceleration due to gravity in fps^2

The velocity due to gravity is calculated by adding the change in velocity (due to gravity) to the former velocity (due to gravity).

Equation (20) describes the total velocity, which is the sum of the sensed velocity due to gravity.

$$VT_t = VS_t + VG_t \text{ in fps} \tag{20}$$

where

VT = total velocity in fps

Figure A-15.- Total position and total velocity computation.

Zonal Harmonics:

FJ(I), I=1,8/ 0.0,0.10826160x10^{-2}, -2.5388x10^{-6}, -1.6560x10^{-6},
-2.1848x10^{-7}, 6.2203x10^{-7}, -3.7624x10^{-7}, -3.4040x10^{-7}/

Sectoral Harmonics:

C(I), I=1,36/ 0.0, 0.0, 2.2181x10^{-6}, -5.0409x10^{-7}, -8.8795x10^{-8},
-5.3098x10^{-8}, 2.5437x10^{-7}, -6.8551x10^{-10}, 1.5765x10^{-6}, 3.1196x10^{-7},
7.6894x10^{-8}, 1.0551x10^{-7}, 7.6476x10^{-9}, 3.1555x10^{-8}, 5.5912x10^{-9},
9.8324x10^{-8}, 5.8692x10^{-8}, -1.4740x10^{-8}, 1.0411x10^{-9}, 3.5092x10^{-9},
1.1576x10^{-10}, -4.0641x10^{-9}, -2.1795x10^{-9}, -2.8471x10^{-10},
-5.8546x10^{-10}, -3.2546x10^{-10}, 4.7452x10^{-10}, -2.0509x10^{-10},
6.7546x10^{-12}, -5.7460x10^{-12}, 1.7718x10^{-12}, -2.4693x10^{-11},
-1.7303x10^{-12}, -3.1326x10^{-13}, 3.3836x10^{-13}, -1.6308x10^{-13}/

Tesseral Harmonics:

S(I), I=1,36/ 0.0, 0.0, 2.8843x10^{-7}, -4.5586x10^{-7}, -1.0960x10^{-7},
2.3455x10^{-8}, 1.0557x10^{-7}, 3.9182x10^{-8}, -9.0602x10^{-7}, -2.2055x10^{-7},
1.4562x10^{-7}, -5.1423x10^{-8}, -4.3734x10^{-8}, 1.1015x10^{-8}, 3.8638x10^{-9},
1.9611x10^{-7}, -1.1854x10^{-8}, -6.9874x10^{-9}, 7.7530x10^{-11},
-2.9593x10^{-9}, -7.6414x10^{-10}, 6.7006x10^{-9}, 4.6325x10^{-10},
-1.7714x10^{-9}, -2.6051x10^{-10}, 7.3081x10^{-11}, -1.6231x10^{-9},
-4.4558x10^{-10}, 1.1795x10^{-11}, 1.4325x10^{-11}, -5.6889x10^{-11},
1.0979x10^{-11}, 8.5920x10^{-12}, 2.4477x10^{-13}, 4.3704x10^{-13},
1.5645x10^{-13}/

Figure A-16.- Harmonic coefficients.

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